

1995 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM
JOHN F. KENNEDY SPACE CENTER
UNIVERSITY OF CENTRAL FLORIDA

521-61

7761
p. 26

THE USE OF A BLOCK DIAGRAM SIMULATION LANGUAGE
FOR RAPID MODEL PROTOTYPING

Dr. Jonathan E. Whitlow
Associate Professor
Chemical Engineering Department
Florida Institute of Technology
Melbourne, Florida

KSC Colleague - Peter Engrand
Computer Science

Contract Number NASA-NGT-60002
Supplement 19

August 18, 1995

ACKNOWLEDGEMENTS

I would like to express gratitude to my NASA colleague Peter Engrand for the opportunity to participate in the Summer Faculty Research Program. In addition, thanks are owed to the Advanced Software group, in particular I am indebted to Charlie Goodrich and Bob Merchant for their help and technical support during my stay. I would also like to extend compliments to Dr. Ray Hosler and Kari Stiles of UCF as well as Greg Buckingham of NASA for providing a professional and stimulating summer program.

ABSTRACT

The research performed this summer focused on the development of a predictive model for the loading of liquid oxygen (LO₂) into the external tank (ET) of the shuttle prior to launch. A predictive models can greatly aid the operational personnel since instrumentation aboard the orbiter and ET is limited due to weight constraints. The model, which focuses primarily on the orbiter section of the system was developed using a block diagram based simulation language known as VisSim. Simulations were run on LO₂ loading data for shuttle flights STS50 and STS55 and the model was demonstrated to accurately predict the sensor data recorded for these flights. As a consequence of the simulation results, it can be concluded that the software tool can be very useful for rapid prototyping of complex models.

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INTRODUCTION

Development of advanced software systems for launch support has been an ongoing task at Kennedy Space Center for a number of years. One launch support system which has received much attention in recent years is the loading of liquid oxygen LO₂ and liquid hydrogen LH₂ prior to launch. Two examples of software which have focused on this particular system is the Knowledge-based Autonomous Test Engineer (KATE) developed by Boeing/INET personnel and the Propulsion Advisory Tool (PAT) developed by Rockwell. The loading of LO₂ and LH₂ are very complex physical systems which have several phases of operation. In addition instrumentation aboard the orbiter and ET is limited due to weight constraints. This makes the task of developing software to analyze these systems for fault detection and diagnosis difficult.

The focus of the ten week fellowship has been to demonstrate the development of a robust model for prediction of physical measurements associated with LO₂ loading. More specifically the model was focused on the flow of LO₂ through the orbiter and into the external tank. The development of the prototype model was accomplished with the block diagram simulation language known as VisSim. This report outlines the development effort and presents the results of several simulations. A discussion of how this model can be enhanced and ultimately integrated into existing software such as KATE and PAT is also given.

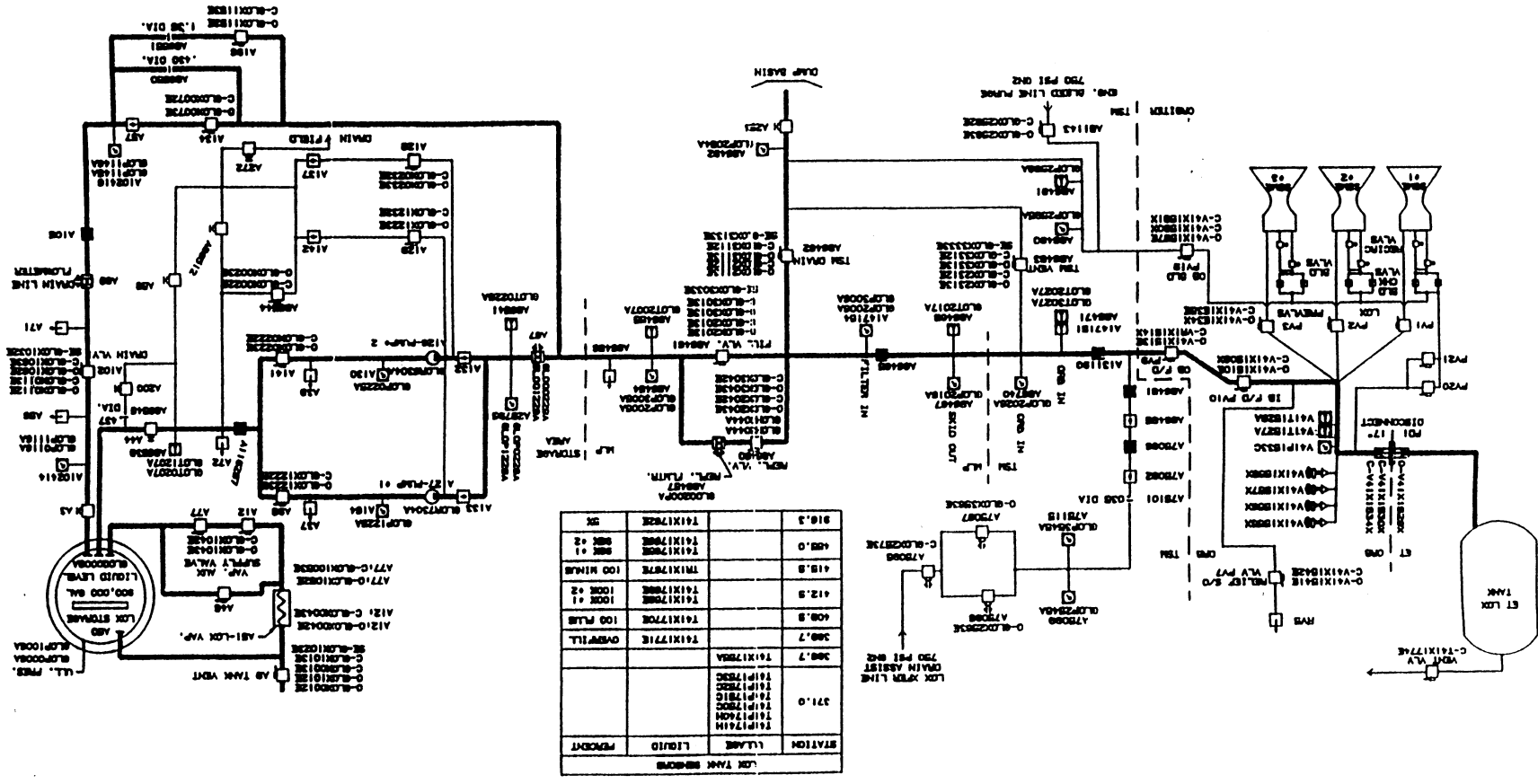
THE PHYSICAL PROCESS

As previously mentioned this work focused on the loading of liquid oxygen into the external tank of the space shuttle prior to launch. Figure 1 gives a process flow and instrumentation diagram for the LO₂ loading system. Because mass aboard the shuttle must be minimized in order to maximize the payload transported into orbit, instrumentation which may be desirable on the LO₂ system for diagnostics (e.g. flow sensors) is limited. This makes the accurate prediction of system variables such as pressure, temperature and flow desirable.

In order to accurately model the physical system the variability in the operating regimes must be accounted for. There are several stages associated with normal LO₂ loading and additional abnormal conditions. The possible operating conditions for LO₂ and typical count down times associated with them are as follows:

- Pump Suction Line Chilldown (T-8:00 to T-6:30)
- LO₂ Transfer Line Chilldown (T-6:30 to T-5:50)
- LO₂ Orbiter MPS Chilldown (T-5:50 to T-5:30)
- Slow Fill ET to 2% (T-5:30 to T-5:15)
- Fast Fill ET to 98% (T-5:15 to T-3:25)
- Topping of ET to 100% (T-3:25 to T-3:20)
- Auto Replenish (T-3:20 to Prelaunch)
- Stop Flow (Abnormal)
- Revert Flow (Abnormal)

3



The chill down periods which are used to condition the transfer system to the liquid cryogen, are the most difficult of all phases in terms of model development. As the cold LO₂ comes in contact with the warm transfer lines and other components, vaporization occurs and two phase flow is encountered. As the LO₂ loading proceeds, the process approaches a thermal steady state and the flow through the transfer system is only in the liquid state. Once the External Tank (ET) is filled, only the mass of LO₂ vaporized from the heat gained through the walls of the tank must be replenished.

As with any physical system which involves the transport of mass and energy, the principals of conservation apply. A conservation of mass equation for the LO₂ ET can be written as:

$$\rho A \frac{dh}{dt} = \rho F_{17" \text{ inlet}} - \rho F_{ET \text{ vent}}$$

where :

ρ = the density of O₂

A = the cross sectional area of the ET

h = the level of LO₂

$F_{17" \text{ inlet}}$ = the flow of LO₂ through the 17" inlet

$F_{ET \text{ vent}}$ = the flow of gaseous O₂ out the ET vent

(1)

Due to the geometry of the LO₂ ET the cross sectional area changes as a function of liquid height and thus must be accounted for. For the conditions modeled (i.e. fast fill through replenish) the liquid density of the O₂ can be assumed constant. In general this is not the case however and hence changes in liquid density would need to be accounted for during non isothermal loading phases (e.g. chill down) The flow of a fluid in a pipe between two points a and b is proportional to the square root of the pressure difference. Thus flow terms in the above equation are defined by the equation:

$$F = \alpha (\Delta P)^{0.5}$$

α = a flow coefficient (admittance)

ΔP = the pressure differential for the section of pipe considered

(2)

For the orbiter section of Figure 1 the flow of liquid oxygen through the orbiter during normal operation can be described by the equation:

$$F_{PV9} = F_{PD1} + F_{PV1} + F_{PV2} + F_{PV3}$$

(3)

In words this continuity equation states that there is no accumulation of liquid in the pipe (i.e. a full pipe) and that the flow into this section through PV9 equals the total flow out of the section through the engine valves PV1, PV2 and PV3 and through the 17" disconnect valve PD1. This equation assumes that the flow is incompressible which is valid for liquid oxygen.

The above equations are the fundamental basis for the development of the predictive models. The procedure of model development was based heavily on loading data from shuttle launches STS50 and STS55. Both of these flights used the Columbia orbiter and in addition used the same launch pad and mobile launch platform. This was desirable from a model building standpoint in order to compare the model against two independent launches while reducing the uncertainty in the physical system.

It should be noted that the system model differs from the actual process in that the engine bleed flows are assumed to branch out from the orbiter inlet as opposed to in the manifold where they actually branch. Although the manifold pressure was calculated from the differential pressure between the ullage and manifold pressures (discussed below) and evaluated for flow prediction, it was not used in the final model. This is due to the fact that the orbiter inlet to 17" disconnect pressure drops gave better model predictions for the flow F_{PD1} given in equation 2.

THE SIMULATION TOOL

VisSim is a block diagram simulation language which can be used to solve both differential and algebraic equations. Modeling equations which describe a physical system are transformed into a block diagram which is numerically solved as a function of time. A graphical interface is provided with pull down menus which allow blocks to be selected and wired together with the use of a mouse. This greatly aides the model building effort in that no program compilation and code debugging is required. In addition, the hierarchal design of the system allows changes to the system model to be readily accomplished.

Other features of VisSim include the use of predefined functions (blocks) which can access other functions or procedures written in C or FORTRAN through user blocks. It also has the capability for Dynamic Data Exchange (DDE) with other applications through DDE blocks. In addition a separate C-code generator and a real time data acquisition package are available as an add on package. Price information for both PC versions and UNIX versions are provided in Appendix A.

MODEL DEVELOPMENT

As previously stated the model building procedure was based heavily on recorded sensor data. Some effort was required to obtain data in the form required by VisSim. Historical flight data which has been recorded and stored on compact disk is readily available. The PC GOAL program which was developed at KSC was used to play back this recorded data and broadcast it over a network. In order to use the data, it first had to be conditioned by recording it to an ASCII file using KATE in the form provided by PCGOAL. A PERL program was then run which could take the recorded file and generate a new ASCII file which could then be read directly into VisSim.

Figure 2 gives the top level of the hierarchal model developed for this work. Each of the blocks given in the Figure represents a combination of additional blocks which describe the individual top level component. The wire connectors and arrows simply represent the flow of information being

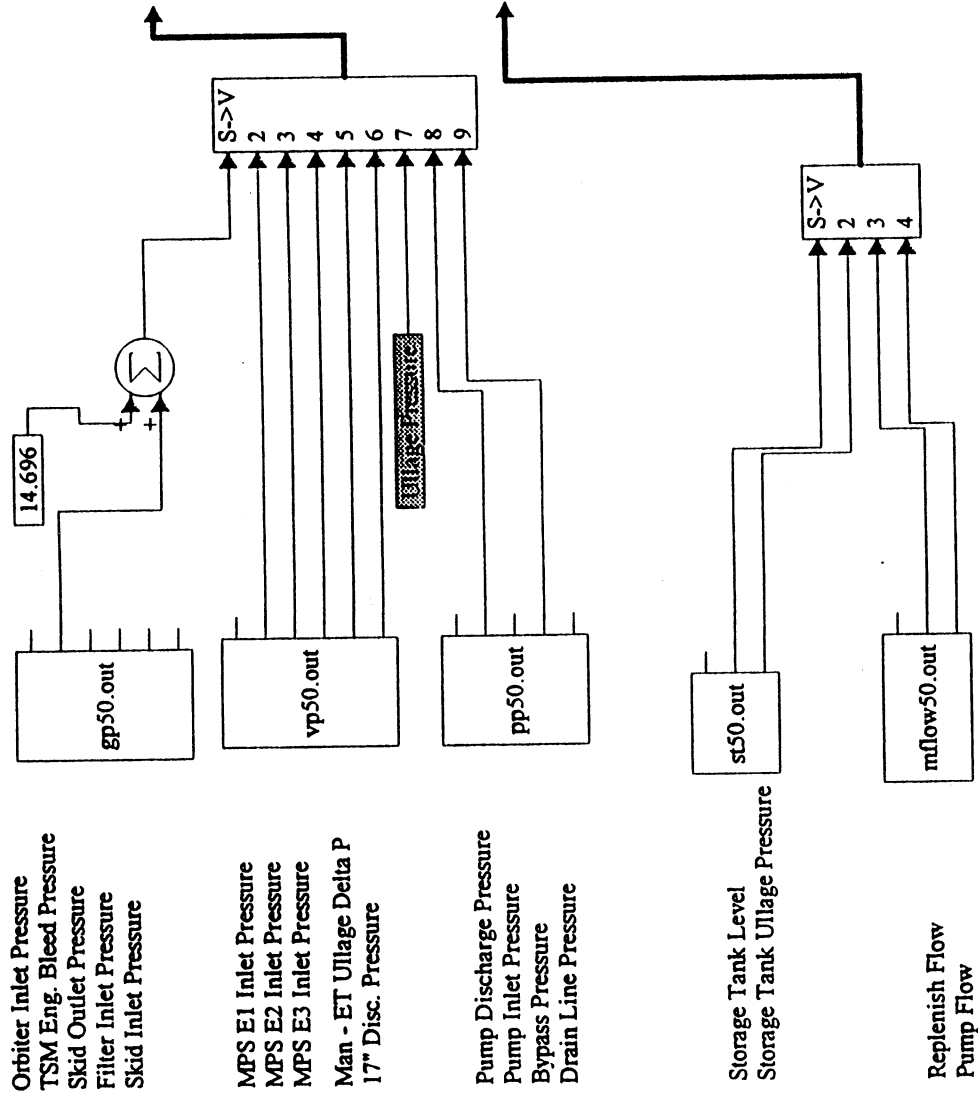


Figure 3 Source Data Block Diagram

The Elevation Adjustment Block

This block which is shown in Figure 4 compensates for the fact that the pressure sensors are located at different elevations. For a static fluid standing in a vertical pipe, the pressure at the bottom of the pipe will be greater than that at the top of the pipe due to the force exerted by the fluid itself. Hence to use the relationship given in equation 2, the elevation difference must be compensated for. The 17" disconnect elevation is used as the zero point to account for elevation differences in the orbiter section. The values given in the constant blocks (5.843, 3.746, etc) which are the elevation corrections in terms of psia (liquid density of 71 lb/ft³), are subtracted from the individual sensor values. The wires are both unbundled with a vector to scalar block and rebundled after the correction with a scalar to vector block.

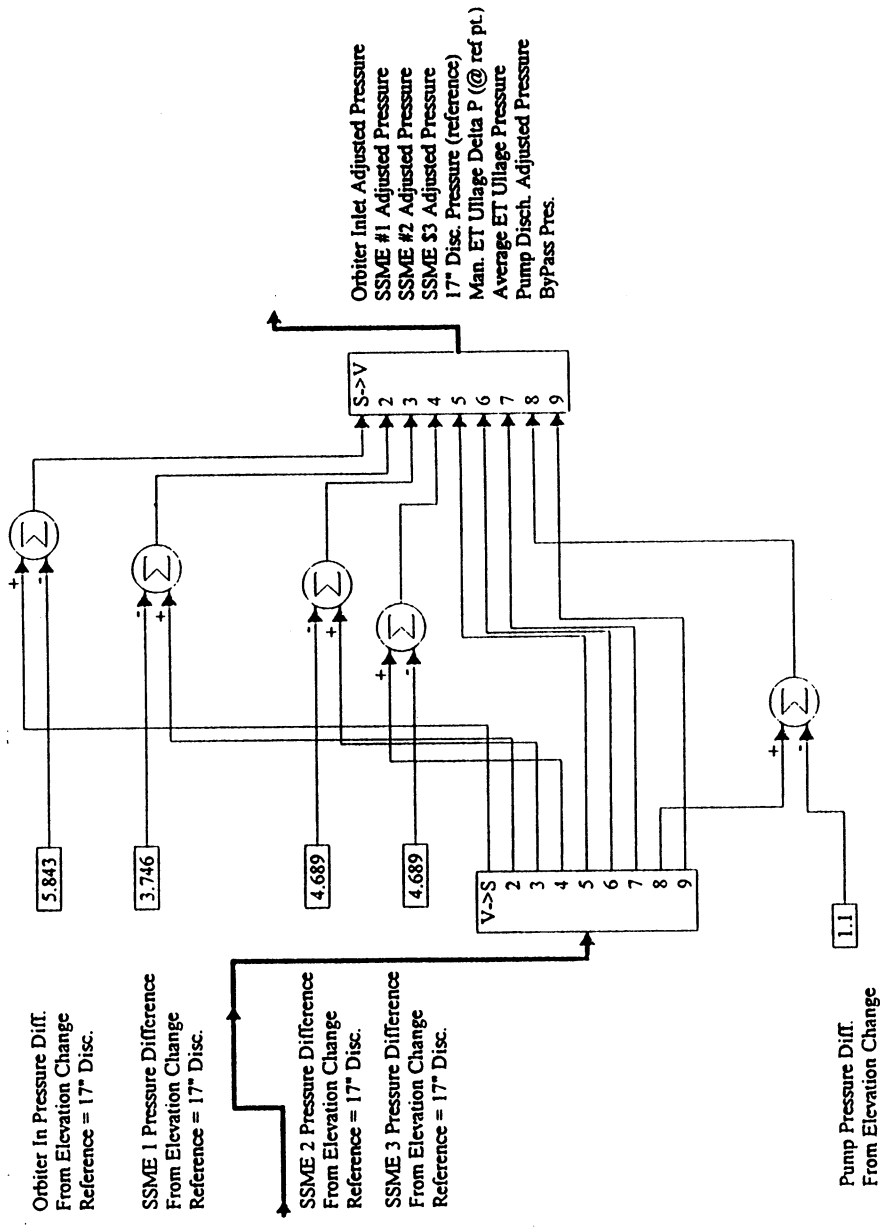


Figure 4 Elevation Adjustment Block Diagram

Delta Pressure Calculations Block

This block which is given in Figure 5 calculates the differential pressures between points of interest (i.e. those in which flow is to be determined). There are 6 separate compound blocks within this block. A typical subblock within this level is given in Figure 6. In this subblock the differential pressure between the orbiter inlet and 17" disconnect is calculated and filtered with a low pass filter. Filters are used in many of the blocks and subblocks throughout the model to reduce the noise in the input data. The variable `filter_start` is defined under the top level Physical Constants / Conversions block and when used in conjunction with the merge block allows the filtered differential pressure to be passed through whenever the simulation time is greater than 50. Initially however, the unfiltered data is passed through. Using this logic avoids the detrimental dynamic effects associated with filtering if there are no previous values to start from in the input data (i.e. the initial pressure would be set to zero instead of the measured pressure). The block `Dsqrt`, which is contained within the subblock, is also used throughout the program and insures that a square root of a negative number is not taken by taking the absolute value prior to the transformation. If the inlet pressure were to be less than the outlet pressure, the flow would be reversed and a negative value would be returned from the block.

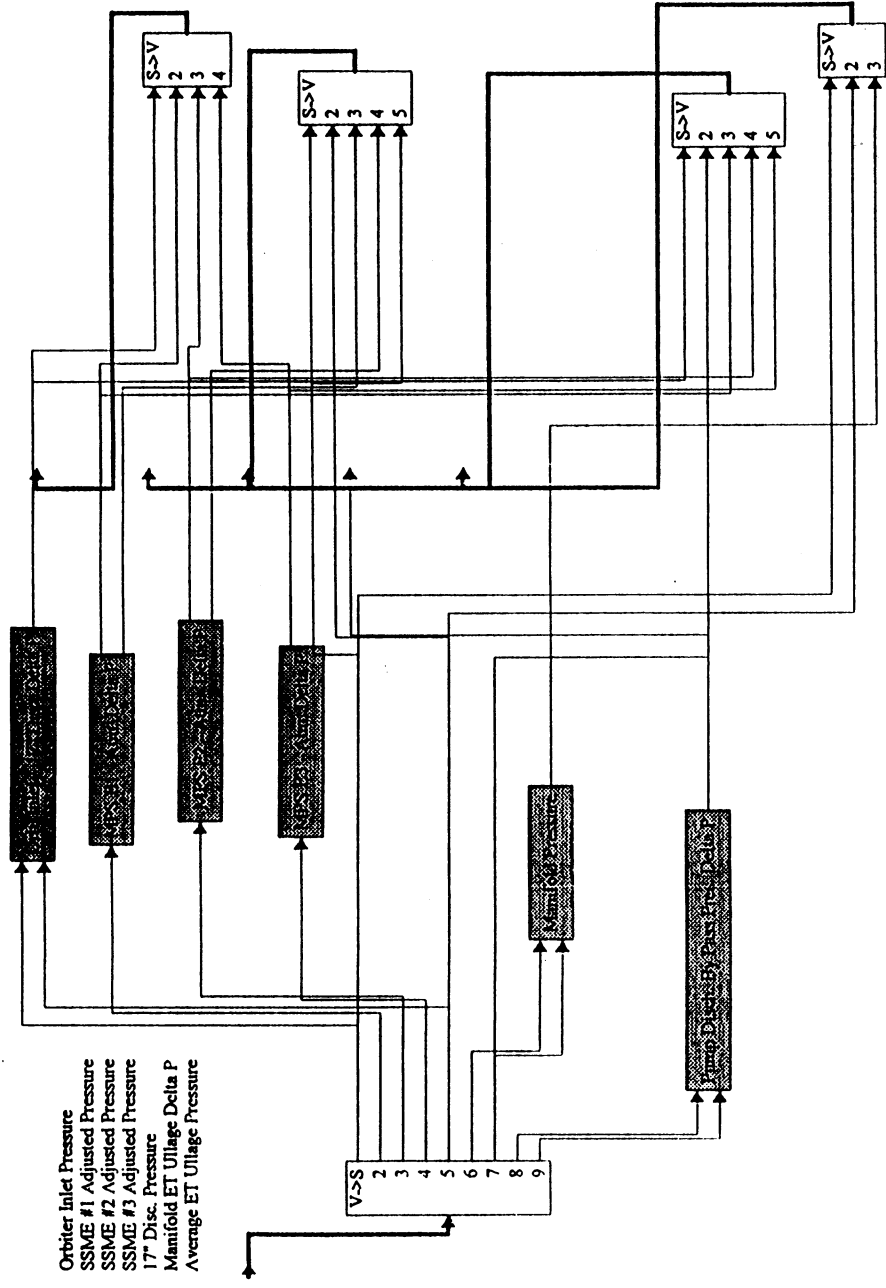


Figure 5 Delta Pressure Calculations Block Diagram

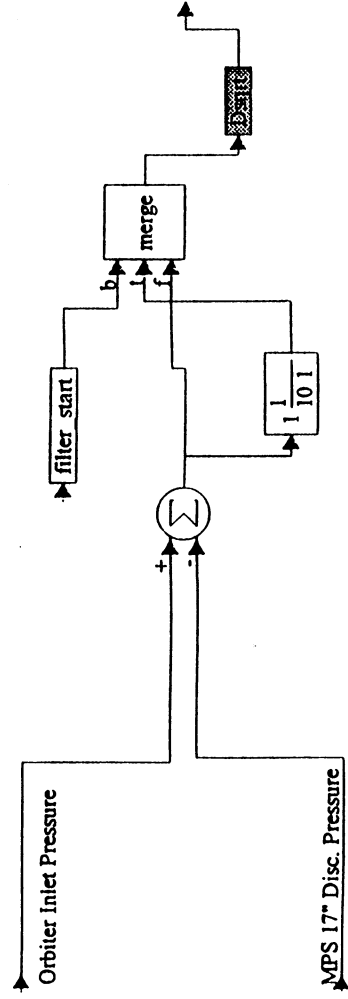


Figure 6 Orbiter Inlet - 17# Disc. Delta P Block Diagram

The other subblocks in Figure 5 consist of one block for each of the engine bleed differential pressures, the calculated differential between the pump discharge pressure and the storage tank recirculation line and the calculation of the manifold pressure. The manifold pressure block does the opposite of the other blocks since the manifold pressure is a differential pressure measurement between the manifold and the ullage pressure. Here the result is obtained by adding the ullage pressure and the barometric pressure (assumed 14.7 psia) to the delta P. Also within the block is a rough estimation of ET level since the differential pressure between the manifold and ullage is proportional to the level of LO_2 .

The engine pressures for SSME #2 and SSME #3 are further corrected for offsets which are introduced into the measurement. These offsets were determined from the loading data so that the corrected inlet pressures for the engines were approximately equal. (i.e. as they should be) The pump discharge to storage circulation is essentially identical to the level given in Figure 6.

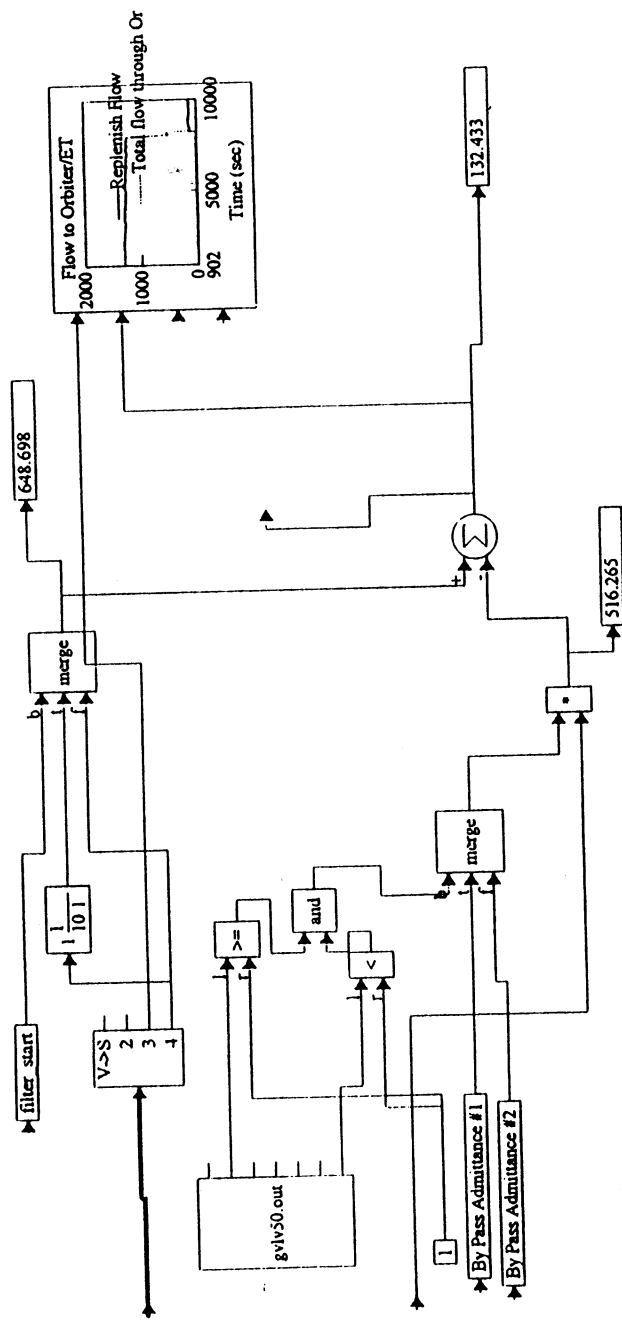


Figure 7 The Pump Mass Balance Block Diagram

The Pump Mass Balance Block

This block which is given in Figure 7 takes the input flow rate as an input and filters it in the same manner that was discussed under the **Delta Pressure Calculations Block**. A mass balance is then performed by subtracting the recycle flow returned to the storage tank. This flow is determined by taking the square root of the differential pressure between the pump pressure and the recirculation pressure calculated from the **Delta Pressure Calculations Block** and multiplying by an admittance value for this line. The admittance can have one of two values depending on whether or not valve A196 (see Figure 1) is opened or closed. As seen in Figure 7, logic is included in the block which examines discrete inputs from a data file (gvl50.out) and when the A196 valve is opened (during topping) a higher admittance value is used to reflect the reduction in resistance in the recirculating line. A plot is also included in this level showing the total flow going to the orbiter/ET once the by pass flow is subtracted. Also included on the plot is the replenish flow. During the replenish model these flows should be equal and this fact was used to determine the admittance value for the recirculating line.

External Tank Mass Balance Block

This block which is presented in Figure 8 contains the core of the model prediction calculations. The flow rate of LO₂ to the ET as calculated from the mass balance discussed in the aforementioned block after subtracting the flow to the engine bleeds (performed in the **Flow Predictions block**) is input into the system. The square root of the pressure drop between the orbiter inlet and 17" disconnect output as shown in Figure 6 is also input and then multiplied by the admittance for this section to also get the flow of LO₂ to the ET. Both of these quantities which should be equal, are converted to mass units and then adjusted for the amount of mass flowing from the ET vent valve (if any). The subblock **#Moles / ET ullage Volume** uses the data for ullage pressure and ullage temperature along with the ideal gas law:

$$\frac{n}{V} = \frac{RT}{P}$$

where :

$$n = \text{lb-moles of oxygen}$$

$$T = \text{temperature (Rankine)}$$

$$P = \text{pressure (psia)}$$

$$R = \text{gas constant } (10.73 \frac{\text{lb-mole psia}}{\text{ft}^3 R})$$

to calculate the molar volume of gaseous oxygen. The mass flow of gaseous oxygen from the vent valve is then determined by multiplying the output from the subblock **#moles/ET Ullage Volume** by the molecular weight of oxygen (32) and the volumetric flow rate of gaseous oxygen. (determined by the Et vent valve admittance and the square root of the etvent to atmospheric pressure drop)

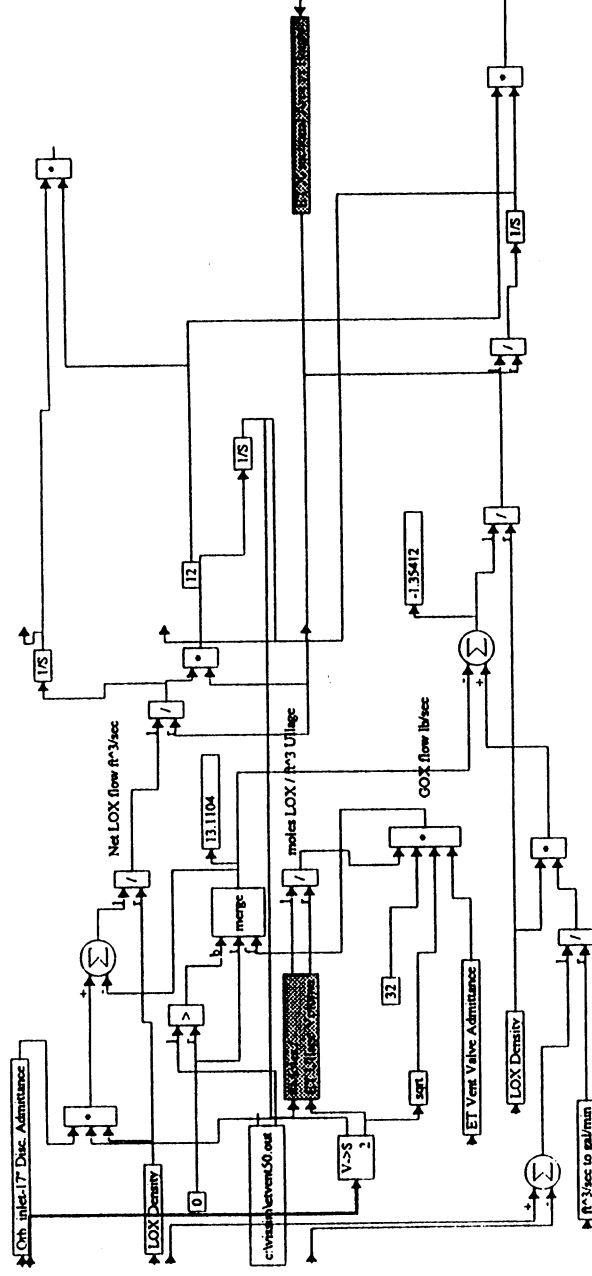


Figure 8 External Tank Mass Balance Block Diagram

The net LO_2 flow into the ET is then determined by dividing by the density of LO_2 and the cross sectional area of the ET. (i.e. a rearrangement of equation 1) The resulting value, which represents the derivative dh/dt is then numerically integrated over time to produce the LO_2 level in the ET. An additional integrator provides the cumulative volume of LO_2 in the ET. This value is fed to the subblock #moles/ET Ullage Volume and subtracted from the total volume of the tank in that block in order to calculate the ullage volume.

The cross sectional area of the tank is determined in the subblock ET X sectional Area vs Height. This subblock consists of a couple of lookup tables using the VisSim Map block. Once the current height is passed to the subblock the approximate area is determined from one these two data tables (depending on the height) as the Map block employs linear interpolation between the known values.

The tables which are contained in the subblock ET X sectional Area vs Height are found in the data files etarea1.dat and etarea2.dat. These files were generated from a separate VisSim program as illustrated in Figure 9. The bottom section of the ET is an ellipse and the equation is given in Et documentation as:

$$\frac{x^2}{165.5^2} + \frac{y^2}{124.125^2} = 1 \quad (5)$$

where :

x = the radius of the tank at any point y

y = the distance below the 124.125 level (i.e. $y = 124.125 - \text{tank bottom}$)

The ellipse describes the geometry of the ET from the bottom of the tank to a height of 124.125 inches. From this point to 220.855 inches the tank radius is approximately constant at 165.5 inches. From 220.855 to the tank top are the ogive sections. An exact equation could not be found for the ogive and a series of equations between discrete points were used based on a conic frustum approximation. The conic frustum assumes a linear change in radius for a given section. (i.e. where the radius is known at the two end points of the section) In reality there is slight curvature over the entire ogive and thus the more sections in which the ogive is divided the more accurate the approximations. The subblocks in Figure 9 perform the conic frustum approximations between the discrete points as indicated by the subblock titles.

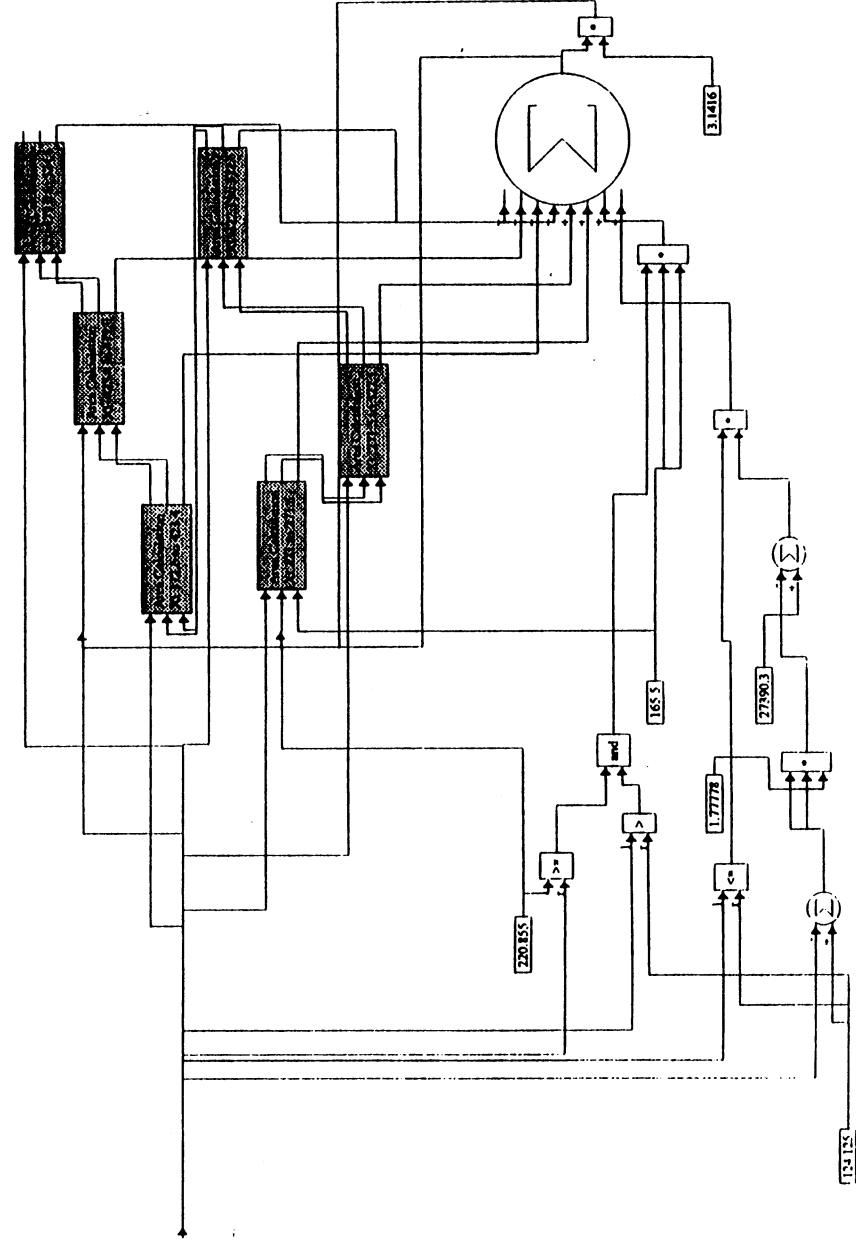


Figure 9 ET X sectional Area vs Height Program Block

Other Blocks

The Flow Prediction, Pressure Prediction, Misc. Plots and Level/Volume Prediction Blocks all provide the graphical results of the simulations. These results are provided and discussed in the next section of this report. The Admittance Values and Physical Constants /Conversions Blocks are self explanatory.

SIMULATION RESULTS

The primary method for determining unknown admittances in the LO₂ loading system was to iterate on system values until the discrete level sensors in the ET (i.e. 5%, 98%, 100-% and 100%) closely agreed with the actual launch data. For STS50 the predicted level in the tank agreed very closely with actual level at the times when the appropriate sensor levels were reached. For STS55 the predicted level was slightly low relative to the data and indicates that some difference exist between LO₂ loading for these flights.

Figure 10 gives the simulation results of how the LO₂ in the ET changes with time for STS50. The level can be seen to rise continuously until the replenish mode is activated at which time the level is maintained relatively constant. It should be noted that even though there is essentially no change in the level at replenish, the numerical integration is still being performed during this phase and thus indicated that flow in to the ET equals flow out of the ET.

The prediction of the flow rate through the 17" disconnect going to the ET is presented in Figure 11 for flight STS 50. As previously discussed, this flow is predicted by both a mass balance and a pressure drop admittance calculation. The mass balance approach gives the more reliable results and was used to determine the LO₂ level in the ET presented in Figure 10. The flow calculation using the pressure differential is very noisy and provides very erratic results including reverted flow during the replenish phase as evidenced in Figure 11.

The prediction of flow for STS 50 through the engine bleeds is presented in Figure 12. The admittance on these predictions was adjusted so the flows would fall in between the 18 - 20 gpm range which is thought to be a close estimate.

The prediction of corrected pressure values for the orbiter inlet, 17" disconnect and engine pressures for STS 50 is given in Figures 13, 14 and 15 respectively. Figures 16, 17, and 18 are the same pressure predictions for the STS 55 flight using the same admittance values. It can be observed that the actual and predicted values for both flights agree in a similar fashion thus validating the model developed. Figure 19 gives the flow rate through the 17" disconnect going to the ET for STS 55. It can be observed that besides predicting a lower level than actually achieved based on the sensor locations, the level is shown to gradually decrease during replenish, thus reconfirming the need for additional data evaluation.

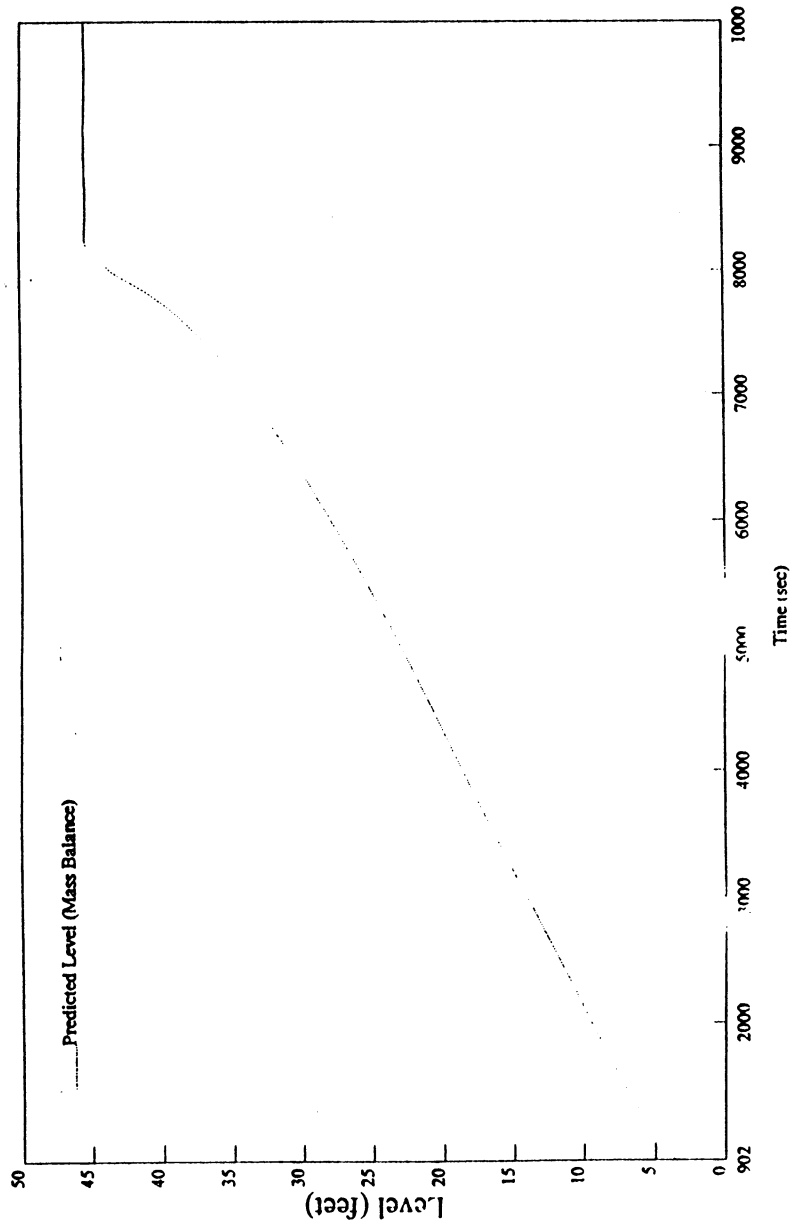


Figure 10 Simulated ET LO₂ Level Vs. Time (STS50)

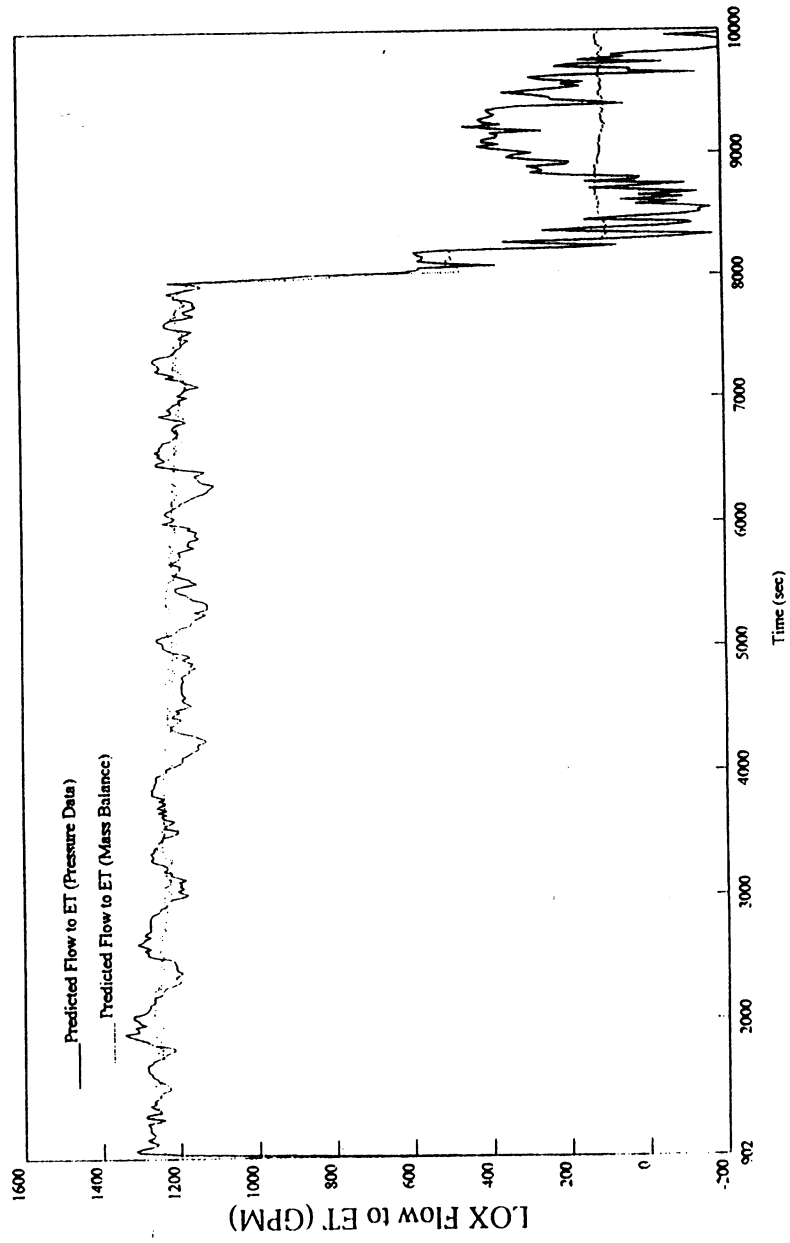


Figure 11 Predicted LO₂ Flow Rates to ET (STS50)

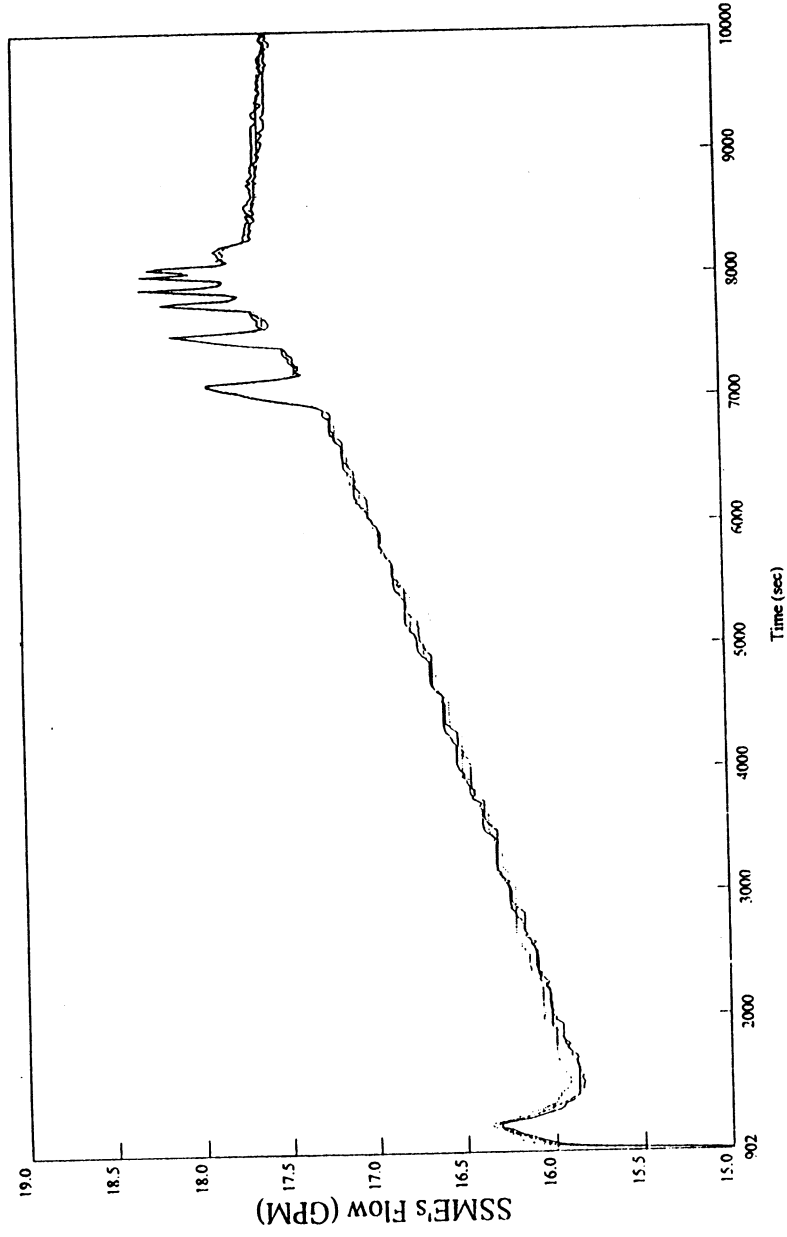


Figure 12 Predicted LO₂ Bleed Flow Rates for SSME's (STS50)

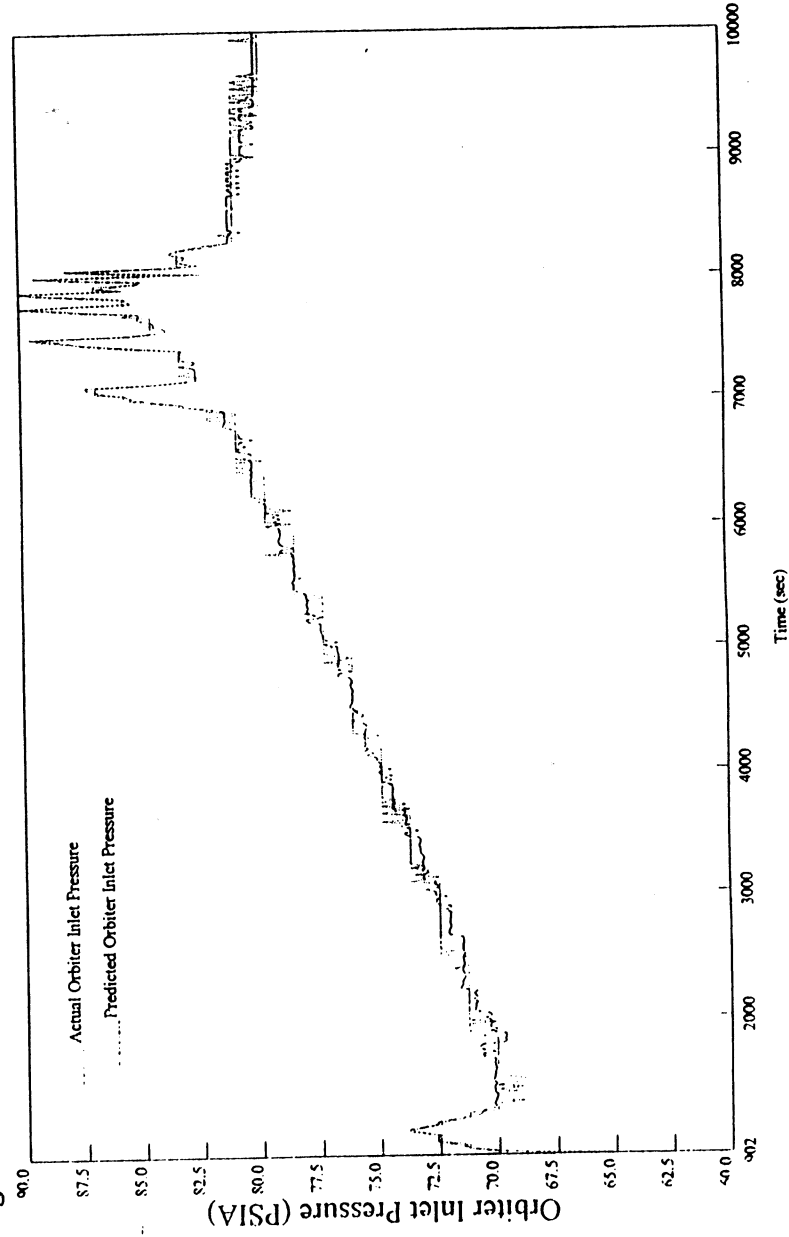


Figure 13 Predicted Vs. Actual Orbiter Inlet Pressure (STS50)

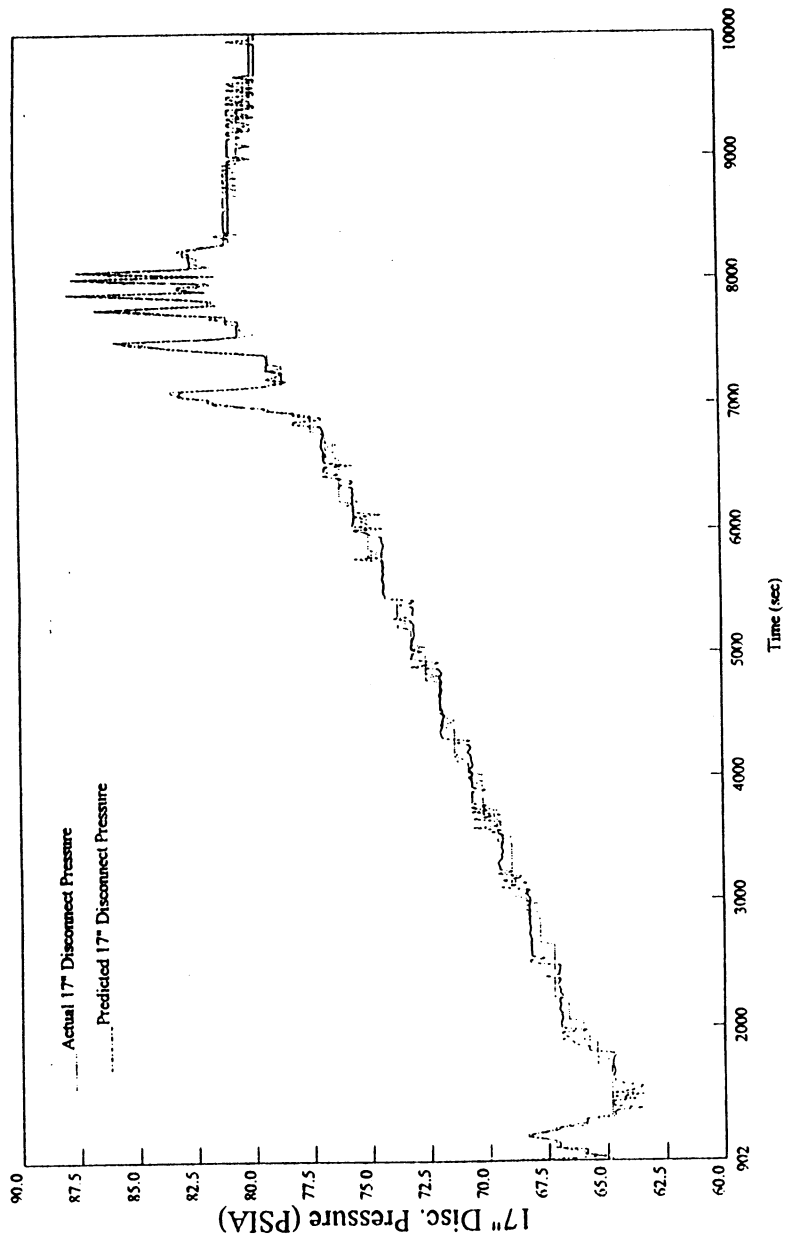


Figure 14 Predicted Vs. Actual 17" Disconnect Pressure (STS50)

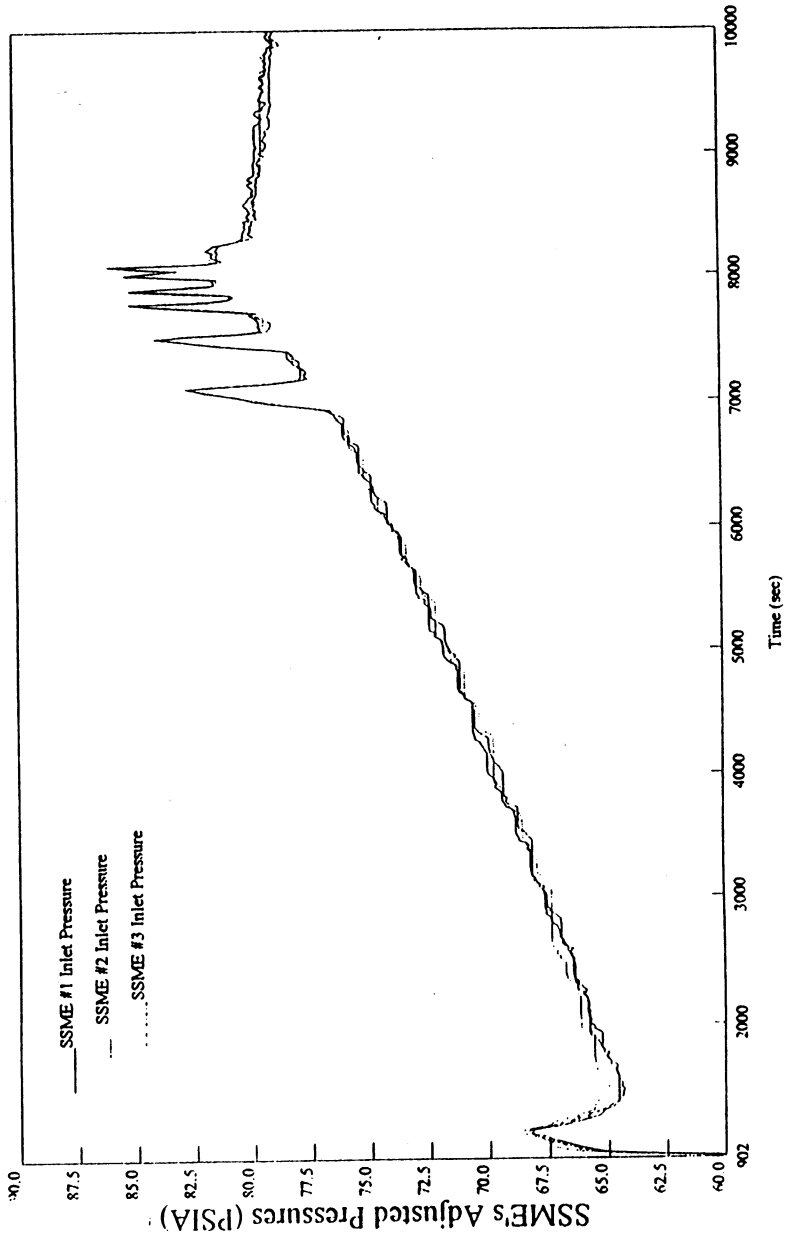


Figure 15 Predicted Vs. Actual SSME Bleed Pressures (STS50)

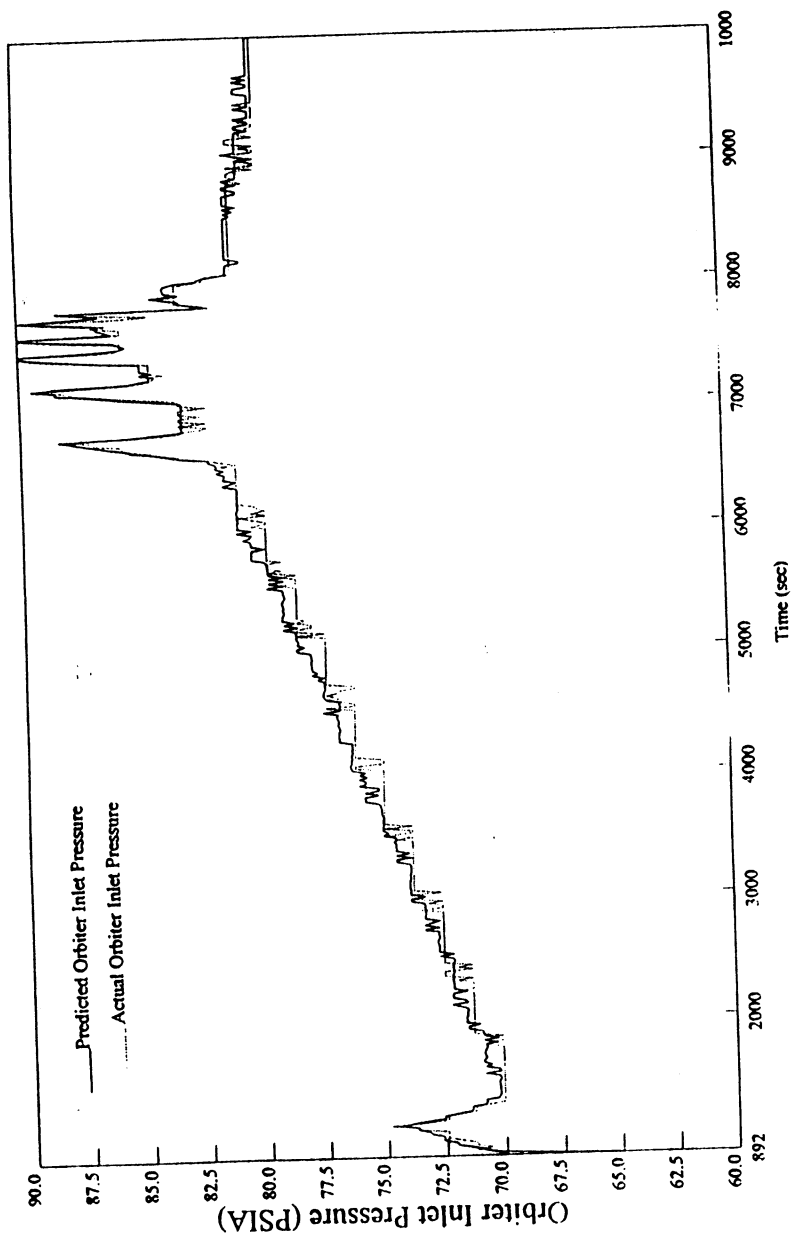


Figure 16 Predicted Vs. Actual Orbiter Inlet Pressure (STS55)

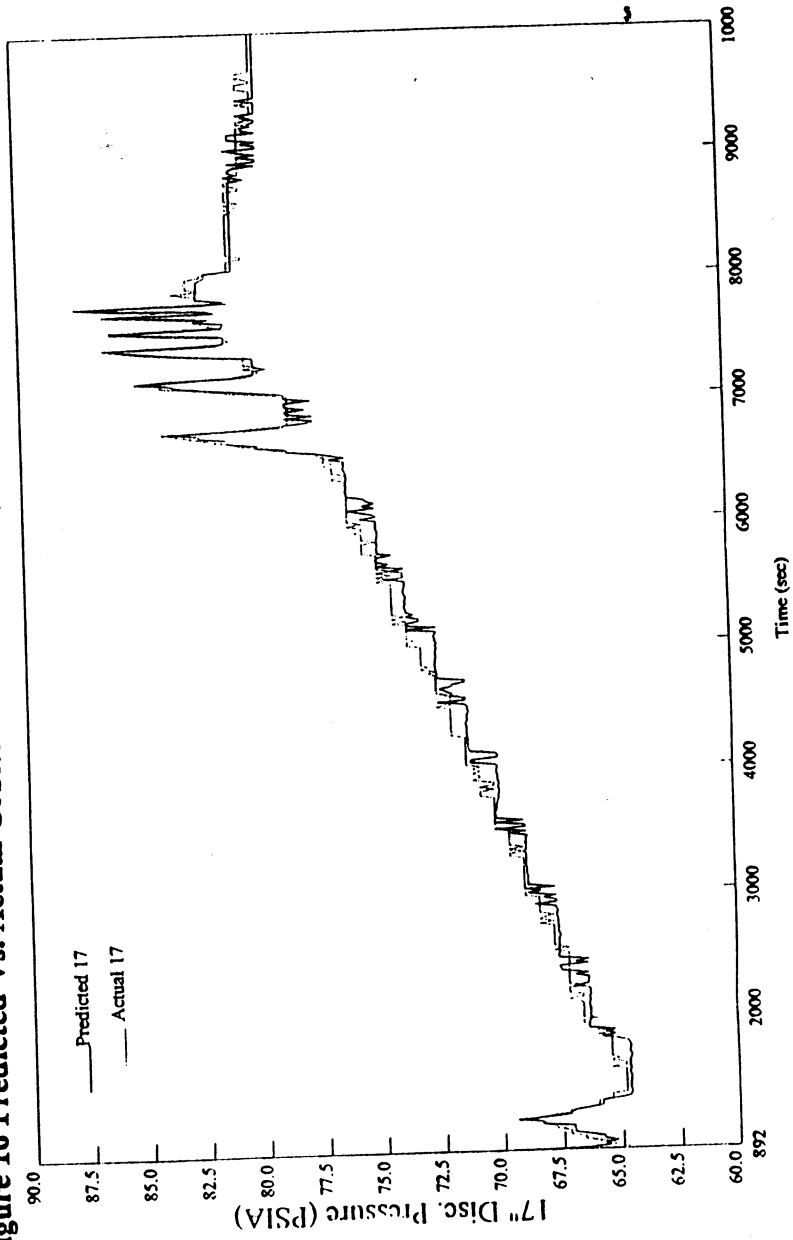


Figure 17 Predicted Vs. Actual 17" Disconnect Pressure (STS55)

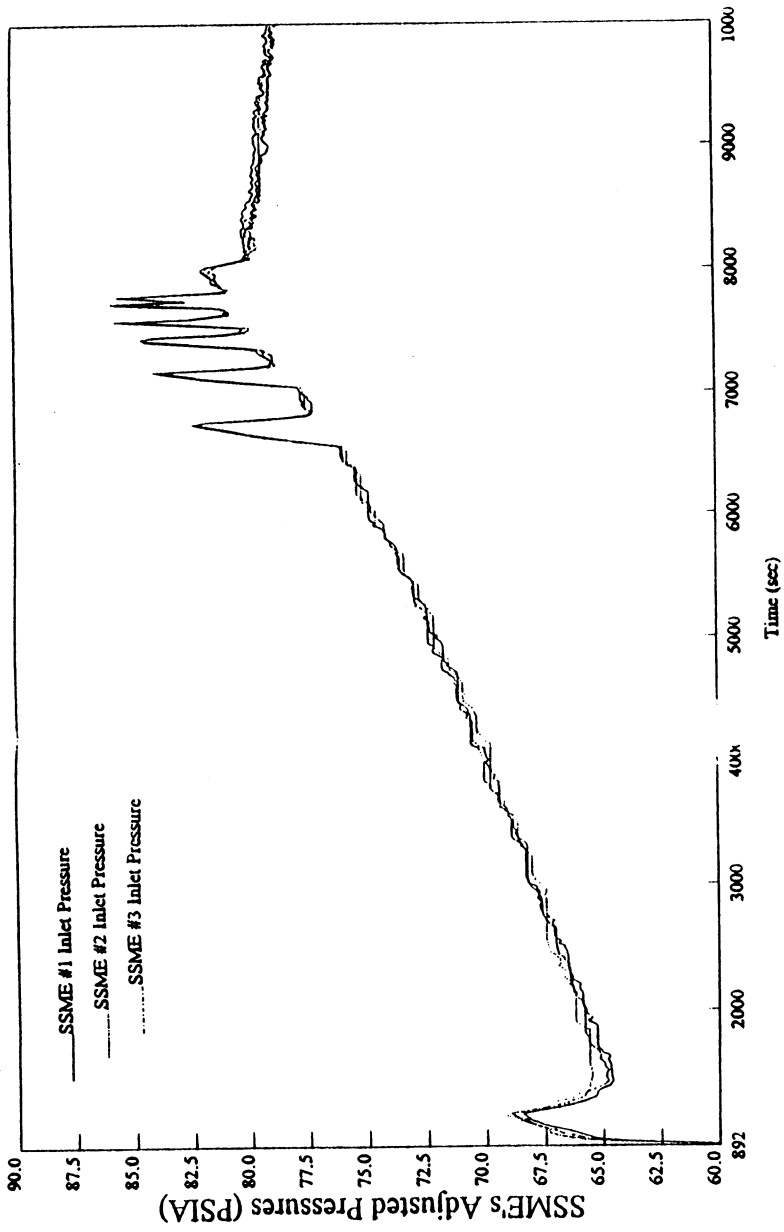


Figure 18 Predicted Vs. Actual SSME Bleed Pressures (STS55)

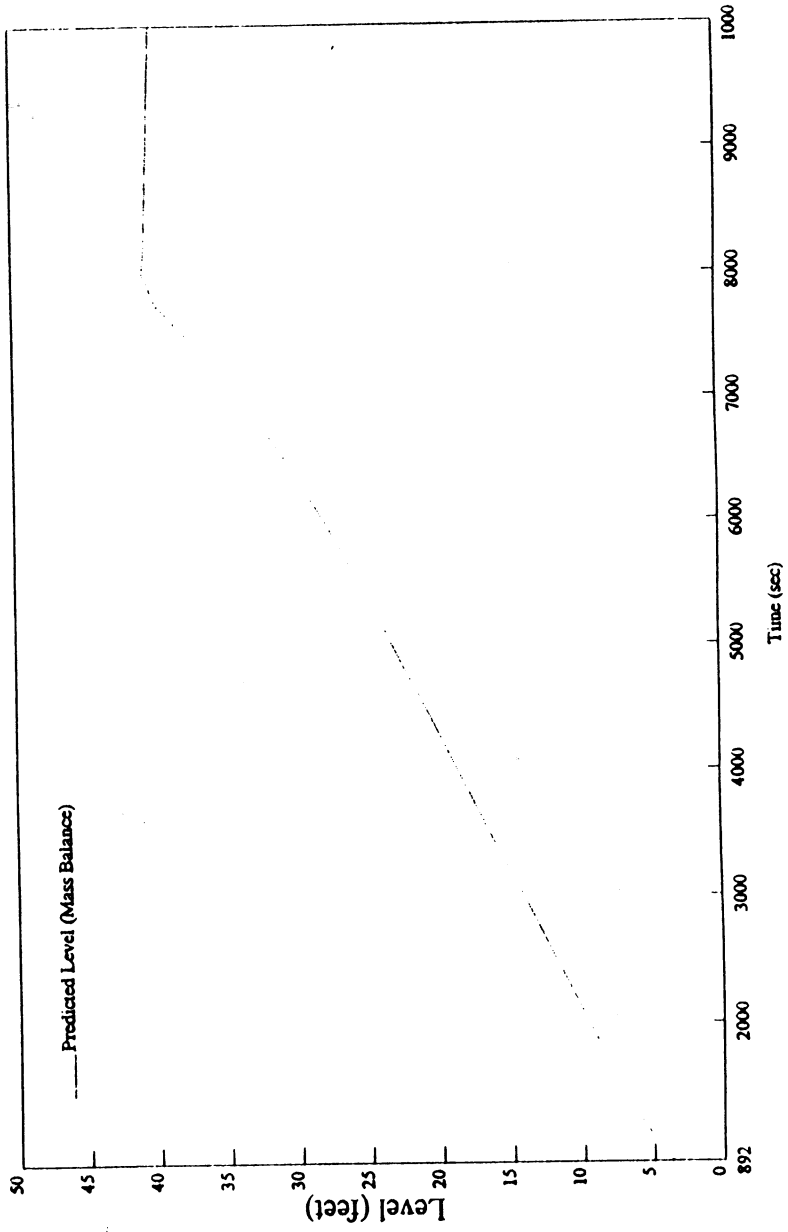


Figure 19 Predicted LO₂ Flow Rates to ET (STS55)

FAULT DETECTION

VisSim can also be used to detect faults within the system by observing the differences between the actual and predicted values and determining whether or not they are within normal tolerances. To confirm that the predicted and actual values would result in discrepancies if a fault entered the process a single point failure was simulated. The results which are shown in Figures 20, 21 and 22 show that the predictive values no longer agree with the actual values at approximately 7300 seconds into the simulation. At this point a false signal was sent to the program that the recirculation valve had opened. As a consequence the admittance was changed on this section of pipe by the program resulting an error in the mass balance when compared to the true process. This error is propagated through the pressure measurements also as evidenced by the plots. When the valve is actually opened at approximately 7650 seconds the predicted and actual measurements agree again.

CONCLUSIONS & RECOMMENDATIONS

The use of VisSim has been shown to be a useful tool for robust and rapid model building of a complex process. The development effort put forth this summer was severely constrained, due to the fact that a personal version of VisSim was employed instead of the upgraded professional version. The personal version is limited in the number of blocks which can be used in the model whereas the professional version has no such constraint. The block limitation became a frequent source of model redesign in order to work within the constraint and thus hampered the development effort.

While the model building effort needs to be extended to cover additional loading regimes and thermal predictions, the current model can serve as the building block for this effort. A professional version of VisSim should be procured before substantial enhancements of the model can be achieved. Additional loadings should also be investigated to determine the effects (if any) of the launch pad, mobile launch platform and orbiter on the predictive models. If differences were encountered as might be expected the model could be adapted (tuned) for each individual launch.

To incorporate the model into an existing software package such as KATE or PAT a mechanism would need to be set up which could link the VisSim application to the existing program. VisSim supports dynamic data exchange and hence may be able to be run in parallel with the existing application. In this manner, pertinent loading data would be passed to the VisSim Environment and the predicted values could either be passed back to the native application or faults could be detected within VisSim and information only passed back when faults occur. If the two processes could not operate in parallel two other options exist; either the model could be encoded into the language native to the particular application or a C-code generator for VisSim could be purchased. The C-code generator would be the more desirable approach as it generates C source code but allows model development to be performed using the graphical block diagram environment.

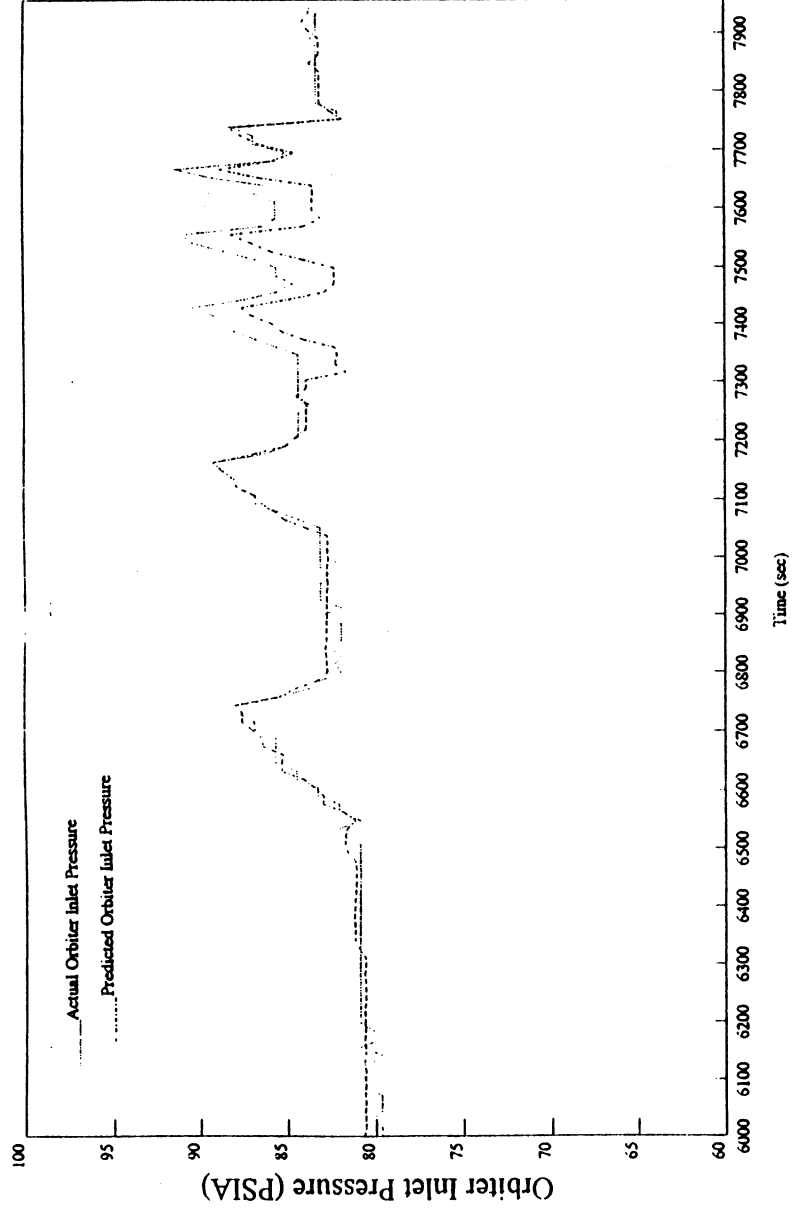


Figure 20 Failure Induced Predictive Error for the Orbiter Inlet Pressure (STS55)

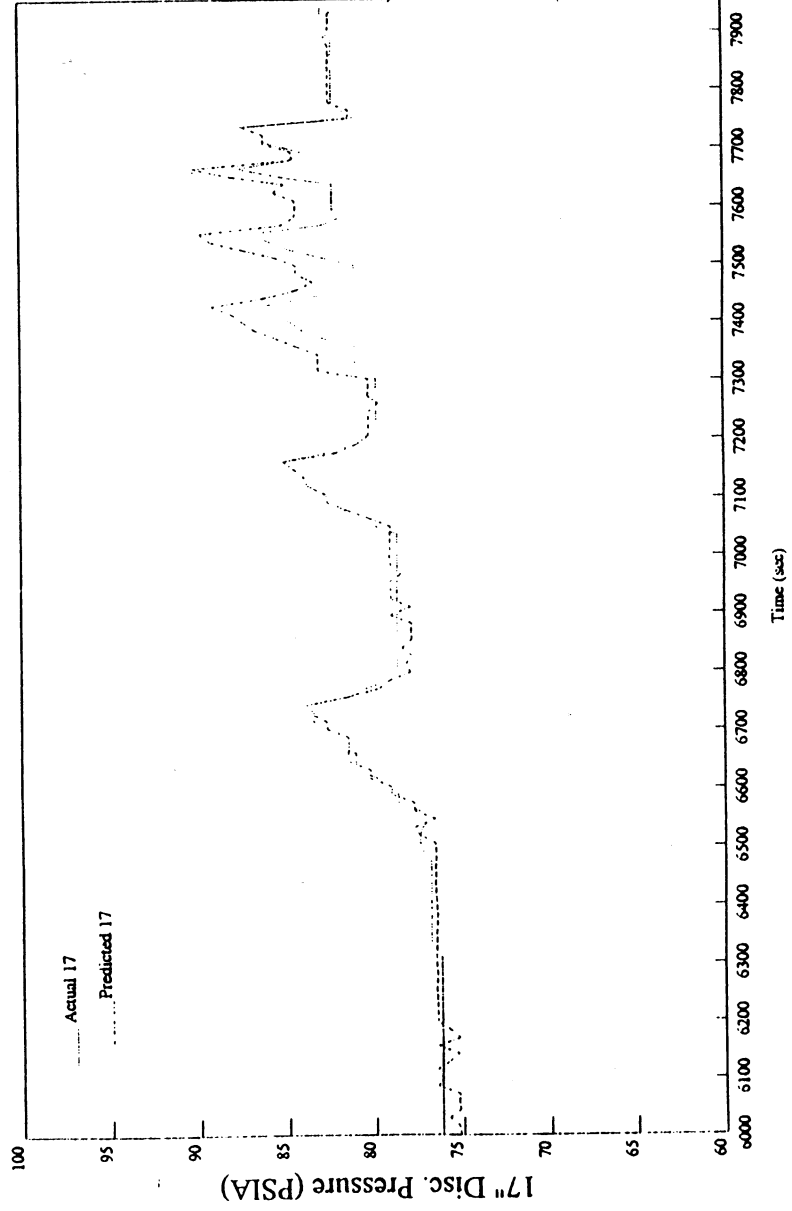


Figure 21 Failure Induced Predictive Error for the 17" Disconnect Pressure (STS55)

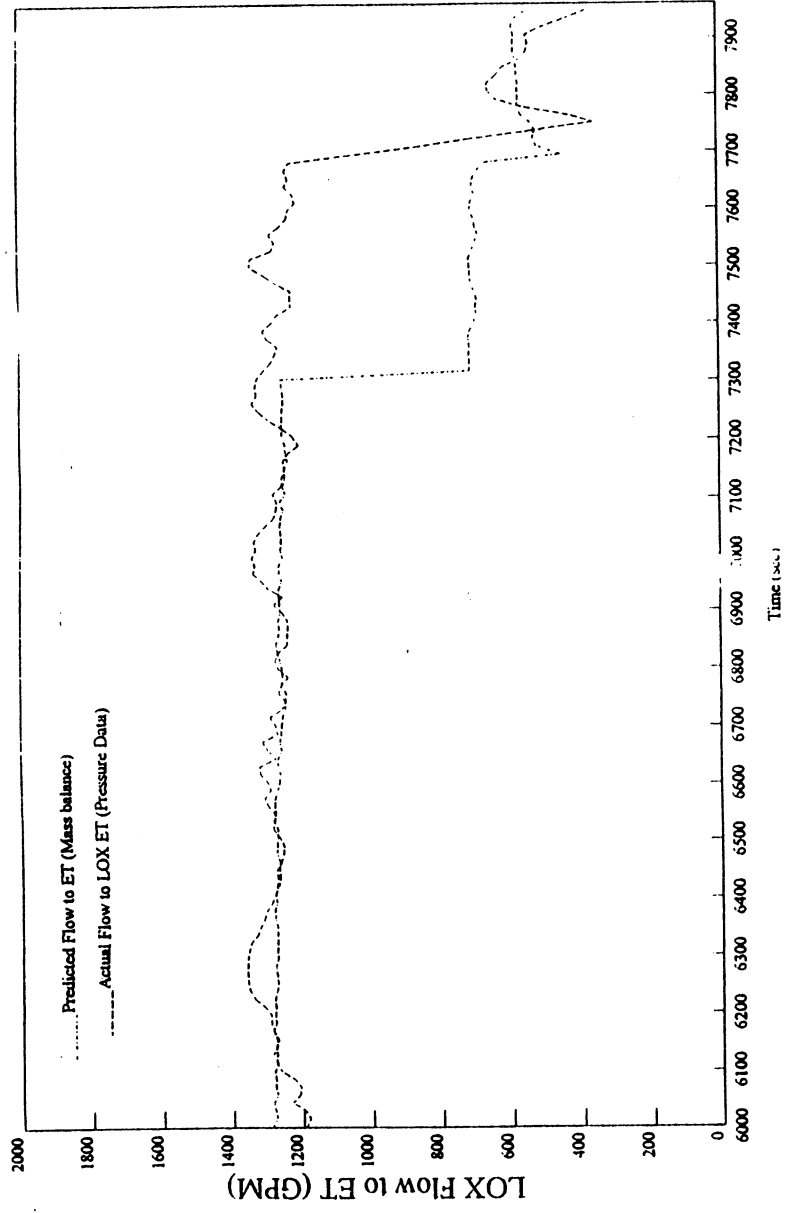


Figure 22 Failure Induced Predictive Error for the LO₂ Flow Rates to ET (STS55)

APPENDIX A

VisSim Prices

Current price information for both the UNIX and PC versions of the VisSim Program and C-code generator is provided below. The academic prices are exact, while the commercial versions are approximate.

	<u>PC</u>	<u>UNIX</u>
VisSim Professional (Academic)	\$595	\$1190
VisSim Professional (Commercial)	\$1795	\$2140
VisSim C-code Generator (Academic)	\$345	\$690
VisSim C-code Generator (Commercial)	\$995	\$1200